The current status of process planning for multi-material rapid prototyping fabrication

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Abstract. Rapid prototyping (RP) is an innovative manufacturing technology. In recent years, the research to fabricate multi-material products by RP is becoming active. In this paper, we update the recent development of process planning for multi-material RP.

Introduction

RP has been identified as "the most innovative and potentially disruptive manufacturing technology in recent years" [1]. Different from conventional forming and machining processes, the technology is an additive build process by adding materials selectively, layer-by-layer, as specified by a Computer-Aided Design (CAD) system. Based on this working principle, various RP machines have been developed, including Stereolithography Apparatus (SLA), 3D Printing (3-DP), Fused Deposition Modeling (FDM), Selective Laser Sintering or Melting (SLS/SLM), and Laminated Object Manufacturing (LOM). In [2], there are some detailed descriptions and comparisons of these RP processing.

Almost all the current RP technologies use a single raw material for model prototyping. Multi-material based products, which have shown broad potentials in various applications, including biomedical, automotive, aerospace, energy, civil, nuclear and naval engineering [3-5], is under active development. Nowadays, some research groups are developing and improving their multi-material RP systems, such as MIT, Carnegie Mellon University, the University of Texas, Drexel University, the University of Michigan and Loughborough University and so on [6-10]. As one of the essential tasks in RP, process planning is used to generate manufacturing process instructions and tool-paths. With two-decade development, the single-material RP and process planning are almost mature. However, process planning for multi-material fabrication in RP is still in its initial stage.

The multi-material process planning gets geometric information and material information from a CAD model to generate fabrication date for RP systems (shown in Fig. 1). Orientation determination, support generation, slicing, and tool-path generation have been identified as four critical tasks for multi-material process planning in RP [11].

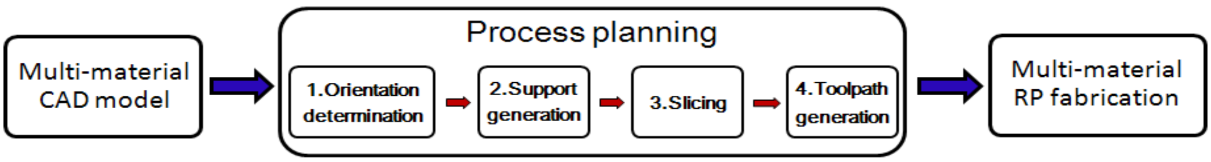

Fig. 1 The task process for multi-material RP technology

- *Orientation determination* is the first step in process planning. Different build orientations for a CAD model will affect the cost and the build time of fabrication. In addition, it also affects the support generation and the total number of slicing layers. The build orientation is usually chosen based on the height of a model, the surface quality, the mechanical properties and the use external support structure [12-13].

- *Support structures* can be divided into external and internal ones, and they are used to support the build material when the build part has a hollow or overhanging structure. It affects the build time, surface quality and mechanical properties of a model. Currently, a lot of support materials have been developed and most of them can be easily solubled and dissolved by water or other liquid materials after fabrication. Some software packages have been developed in this research area to automatically generate the support of RP fabrication, such as Materials's Magics RP and Marcam Engineering 's VisCAM RP, etc. [14-15].
- *Slicing* is to transfer 3D CAD solid model to a 2.5D horizontal plane with a layer thickness, which is normally divided into uniform slicing and adaptive slicing. In uniform slicing, the distance between two consecutive layers is the same; in adaptive slicing, the distance between two layers varies depending on the surface curvatures of the CAD model. It affects the time of fabrication, surface quality and mechanical properties. If the slice is too thick, the time to fabricate is reduced but the accuracy of the object is poor. On the other hand, the surface quality is good but the time is increased [16]. Compared with uniform slicing, adaptive slicing can better balance the build time and the surface quality of RP fabrication.
- *Tool-path* is the trajectory of nozzles or print heads during a RP process to fill the interior of the layer. It includes the determination of the topology, geometry and material of the tool-path, the generation of the appropriate tool-path and determination of process parameters [16]. There are two main types of multi-material tool-path patterns: Zigzag and Contour patterns, as shown in Figure 2. In selecting the multi-material tool-path pattern, we consider not only the build time and cost, but also the surface quality, strength and stiffness of a model, materials bonding characteristics and warpage of the final model.

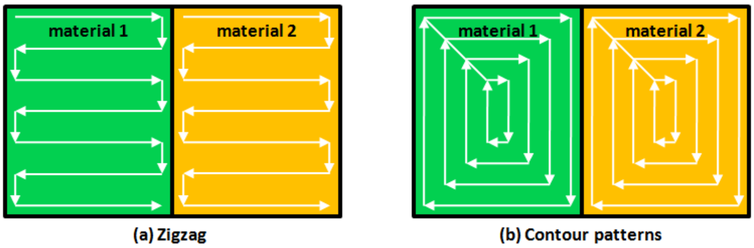

Fig. 2 Two main types of multi-material tool-path patterns.

Research Issues of Multi-material Process Planning

Compared with the task of single-material based process planning, the task of multi-material process planning is more complex and difficult. It requires to consider geometric and topological information as well as material information. Several new problems need to be addressed. For instance, whether the build orientation is suitable for fabricating multi-material models in RP, and can we still use one support material to support different build materials? How can we decide the thickness of slicing and generate tool-path to fill the interior of the layer when there are different materials in one layer? Do we need to modify the manufacturing process for multi-material RP?

A few researchers have done some works of slicing, tool-path generation and the fabrication process for the fabrication of multi-material models using RP. In the following sections, we will give a more detailed description from these three research aspects.

The Fabrication Process. In the multi-material RP processes, apart from the geometry and topological information, process planning gets material information from a CAD model. It makes the process planning to address one more parameter – material element. Meanwhile, owning to the continuously internal cavities and material composition in each layer during fabrication, it is quite time-consuming and difficult to fabricate a multi-material model with good surface quality and cost. Therefore, it is vital to develop methods to optimize the fabrication process in the multi-material RP to minimize the build time and improve surface quality. Table 1 shows some approaches for the fabricating process in multi-material RP.

Table 1 Different approaches for the fabricating process in multi-material RP.

Methods	*Refs*
It describes a process method for fabrication multi-material models in RP, and the difference between traditional process planning and the proposed approach is also highlighted in this paper.	[11]
It describes a process planning method for a virtual simulation system (VSS) of FDM in RP. In this system, people can check or test a variety of the RP process parameters to make the best selection of multi-material tool-path and other parameters.	[17]
A novel process planning algorithm with an extensible markup language (XML) format is introduced. It contains geometry, topology, material and manufacturing information to generate a process for the fabrication of multi-material RP models.	[18]
It describes a feature based design and process planning for fabricating multi-material models in RP. It enables the identification of fabrication strategies, including orientation, slicing, road width, deposition path, etc.	[19]
It presents an approach to process multi-material models by integrating material information along with geometry information in CAD model.	[20]

Slicing. Adaptive slicing has a lot of advantages compared with uniform slicing. It can reduce the build time and improve the surface quality though the varied distance between two layers. In recent years, to generate adaptive slicing is the trend in this research area.

In the single-material RP fabrication, some adaptive slicing algorithms have been developed based on the curvatures of the CAD modal surface [21-22]. That is, the greater the curvature is, the smaller the thickness of layer is. However, a multi-material CAD model is comprised of two or more materials, and it includes not only the geometry information but also the material information. As thus, it is necessary to consider the material changes when slicing the multi-material CAD model in RP. Table 2 shows some adaptive slicing approaches for fabricating multi-material models in RP in recent years.

Table 2 Different approaches of slicing for multi-material objects in RP

Methods	*Refs*
It describes an information pathway for multi-material fabrication in RP, in which the slicing considers both geometry information and material information of a CAD model.	[23]
It is adaptive slicing based on geometrical and material variation. The minimum and maximum layer thickness of a multi-material model are considered as well.	[24]
It applies dexel encoding for directly slicing multi-material assemblies in RP to provide better surface quality and accuracy.	[25]
A contour sub-division algorithm is depicted to form slicing for multi-material models. In every slicing, the grading of a material is decomposed into sub-contours through different grading variations, which process makes different thickness of layers.	[26]
It is an adaptive slicing method with the geometric contour constraint for a multi-material model. It can accurately guarantee the slicing boundary information and multi-material information in the slicing processing.	[27]

Tool-path Generation. Owning to the continuously varying material composition in each layer and between layers, it is really a difficult task to generate multi-material tool-path. It is necessary to consider the relationship between different materials and the continuous changeover sequence of materials or nozzles during fabrication. In the same time, it needs to avoid the collision of different tools, reduce the fabrication time, and improve the surface quality and mechanical properties and so on.

In recent years, some methods and algorithms have been developed to generate multi-material tool-path in RP (shown in Table 3).

Table 3 Different approaches to generate tool-path for multi-material objects in RP

Methods	*Processing*	*Refs*
An overlap-detection algorithm to fabricate a two-material model with the least changeover of materials, which process reduces the time of fabrication enormously.	SLA	[28]
A topological hierarchy-sorting algorithm to generate tool-path by grouping slice contours into families connected by a parent and child relationship. It increases the fabrication efficiency and avoids the redundant tool movements and potential collisions.	VSS	[29]
An in-house intelligent multi-material tool-path generation system to fabricate high quality models.	VSS	[30]
A morphing based approach to generating tool-path to build multi-material models to mitigate the limitation for fabricating multi-material models in RP.	Blend Manufactur e System	[31]
A multi-nozzle path algorithm to increase both spraying efficiency and accuracy for multi-material fabrication in RP.	RP	[32]
An algorithm to generate tool-path to be used to promote robust and efficient for multi-material fabrication in RP.	RP	[33]

Conclusions and Future Works

Process planning for multi-material enables RP to directly fabricate multi-material models. In this paper, the critical task for multi-material process planning in RP is introduced. The literature of multi-material process planning for RP is updated according to the following three aspects: process of fabrication, slicing and tool-path generation.

Further research is expected in the following aspects.

- The RP process planning is relatively time-consuming and uneconomical, in particular for complex multi-material models. It is beneficial to develop more efficient and intelligent methods and algorithms for orientation determination, support structures, slicing and tool-path generation for multi-material RP fabrication.
- As orientation determination, support generation, slicing and tool-path generation are interacted between each other, it is timely to integrate these four tasks into one software platform to optimize the process planning for least time and cost for fabrication multi-material models with the highest surface quality simultaneously.

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